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DYNAMIC SIMULATION OF CFRP STRENGTHENED STEEL COLUMN UNDER IMPACT LOADING

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ABSTRACT

Carbon fibre reinforced polymer (CFRP) strengthening of metallic structures under static loading has shown great potential in the recent years. However, steel structures are often experienced natural (e.g. earthquake, wind) as well as man-made (e.g. vehicular impact, blast) dynamic loading. Therefore, there is a growing interest among the researchers to investigate the capability of CFRP strengthened members under such dynamic conditions. This study focuses on the finite element (FE) numerical modelling and simulation of CFRP strengthened steel column under transverse impact loading to predict the behaviour and failure modes. Impact simulation process and the CFRP strengthened steel column are validated with the existing experimental results in literature. The validated FE model of CFRP strengthened steel column is then further used to investigate the effects of transverse impact loading on its structural performance. The results are presented in terms of transverse impact force, lateral and axial displacement, and deformed shape to evaluate the effectiveness of CFRP strengthening technique. Comparisons between the bare steel and CFRP strengthened steel columns clearly indicate the performance enhancement of strengthened column under transverse impact loading.

KEYWORDS

CFRP, impact loading, finite element analysis, steel column, model validation.

INTRODUCTION

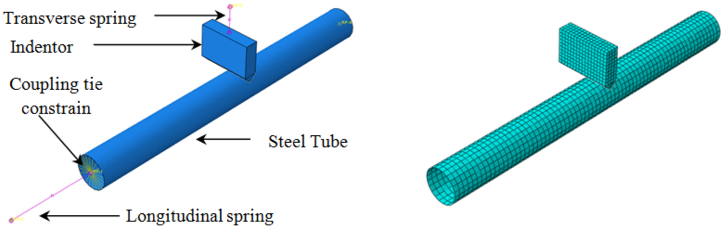
Carbon Fibre reinforced polymer (CFRP) composites have gained wide acceptance in civil engineering applications due to their unique advantages such as high strength-to-weight ratio and excellent corrosion resistance over the past few decades. The use of CFRP in concrete structures is a well proven technique. More recently utilization of CFRP composite to strengthen existing steel structures has drawn attention to the researchers. The significant advantages and mechanical properties of CFRP can be an excellent alternative for rehabilitation and strengthening of steel structures. A considerable amount of research works have been carried out since last couple of years to explore the advantages of CFRP strengthening technique of steel members. Experimental tests have been reported in a number of works (Fawzia et al. 2013; Haedir et al. 2011; Bambach et al. 2010; Fawzia et al. 2006; Shaat and Fam 2006). The results showed the enhanced performance of strengthened members compared to unstrengthened members. Extensive finite element (FE) analyses also carried-out to predict the behaviour of CFRP strengthened steel members under static loading (Deng et al. 2004; Fernando et al. 2009; Zhang and Teng 2010). However, compared to the static loading conditions a little progress is achieved on the behaviour of CFRP strengthened steel members under dynamic loading. Bambach et al. (2009, 2010) conducted experimental and analytical studies on steel-CFRP tubes and aluminium-CFRP beams under axial impact and transverse blast loading. Results obtained from these experiments have shown significant enhancement of energy absorption and load carrying capacity of strengthened specimens compared to the bare specimens. Steel tubular columns are used extensively in underground and multi-story car parks, bridge piers, overpass bridges, roadside buildings, utility poles and others. These structural members often experience dynamic impact loading from moving vehicles, heavily loaded ships and natural dynamic loading. Recent studies and statistical data have shown that accidental vehicular collision is a major cause of roadside building and bridge collapse. However, knowledge is very limited about the behaviour of CFRP strengthened columns under transverse impact loading. This paper presents the finite element (FE) numerical modelling technique and analyses of CFRP strengthened square hollow section steel columns under transverse impact loading.

NUMERICAL MODELLING

The objective of this study is to investigate the performance of CFRP strengthened steel columns under transverse impact loading which is the most likely cause of structural failure due to vehicular/ship impact. FE numerical models are developed and validated to ensure reliable modelling and analysis results. The current simulation and validation are conducted in two steps due to lack of experimental results of CFRP strengthened steel columns under transverse impact loading. The first phase is validation of impact simulation process and the second phase is validation of CFRP strengthened steel column. Later impact simulation will be performed using the validated CFRP strengthened column model.

Dynamic Impact Simulation

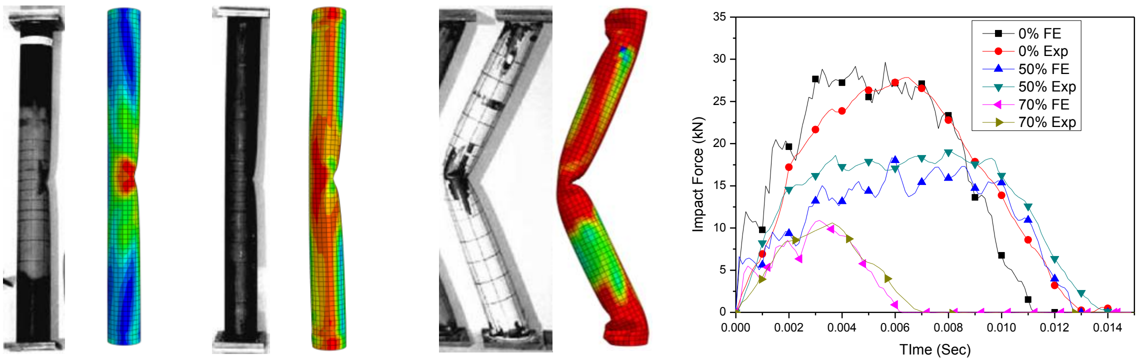
Dynamic transverse impact simulation is conducted using ABAQUS/Explicit (SIMULIA, 2011) software package. Initially axially loaded circular hollow section (CHS) steel tubular column has been modelled and analysed under transverse impact loading. The results are compared with the drop weight impact test conducted by Zeinoddini et al. (2002) to ensure that numerical modelling and analysis process is accurate. The present numerical model is developed using four different parts: CHS steel tube, the drop mass impactor, transverse spring, longitudinal spring. The conventional shell element (S4R) and the 8-node solid element (C3D8R) are used to model steel tube and drop mass respectively. The both types of element available in ABAQUS library are capable of adopting reduced integration and overcoming hourglass numerical problem. The steel material properties are adopted form the experimental tests (Zeinoddini et al. 2002). The CHS steel tube used by Zeinoddini et al. (2002) was high tensile steel with a tensile strength of 500 MPa. Thus, no strain rate effect is considered in the steel material as high tensile steel show less sensitivity to strain rates (Jones, 1997). The support conditions of axially loaded CHS are assigned to keep it consistent with the experimental tests. The right end of the tube is fixed by introducing reference point at the centre of the hollow section. However, the axial spring is deployed at the left end to apply axial loading during the analysis process as shown in Figure 1. A transverse spring with negligible stiffness is also modelled to consider frictional effect as observed in the experiment (Zeinoddini et al. 2002). During the analysis, axial load is firstly applied in quasi-static manner at the left end of the longitudinal spring during the first natural period of the tube. The smooth amplitude option is used to apply the axial load as displacement control approach. The stiffness and applied displacement of the spring are adjusted to induce 50%, and 70% of the steel tube squash load at the right end of the spring. After applying the axial loading, the impact loading step is initiated and the contact interaction is developed between the sharp edge impactor and the outer surface of the tube. The surface to surface contact option is used to model the contact interaction and the initial impact velocity is calculated as 7 m/s.



(a) (b)

Figure 1. (a) Simplified numerical modelling; (b) Finite element meshing

Figure 2(a) shows the failure modes comparison of current impact analysis and the test results. Good agreements between the FE analysis and test results are achieved. At 70% axial loading CHS tube shows global failure behaviour with large lateral and axial displacements as noticed in the earlier experimental tests (Zeinoddini et al. 2002). Furthermore, the current FE analyses successfully predict the impact force-time responses at 0%, 50% and 70% axial loading as shown in Figure 2 (b).



Test FE Test FE Test FE (b)

0% Axial load 50% Axial load 70% Axial load

(a)

Figure 2. (a) Failure modes comparison (test conducted by Zeinoddini et al. 2002); (b) Impact force-time histories comparison

Validation of Numerical Model

Three-dimensional FE models of square hollow section (SHS) bare steel and CFRP strengthened steel columns are developed to validate with Shaat and Fam (2006) axial compression tests. The detail of the model geometry and CFRP warping schemes can be found in Shaat and Fam (2006). Figure 3(a) depicts the detail of the FE model including steel column with shell elements, solid end plate and composite layers (CFRP and GFRP). The tie contact is used to connect the steel surface and composite laminates of strengthened columns. No adhesive element is modelled as each lamina is prepared by wet lay up of dry fabric with resin. The boundary conditions are applied to attain pin-pin support as observed during the test. Initially the buckling analysis is performed to predict the first buckling mode of the column followed by a non-linear static analysis considering both material and geometric nonlinearities. The axial load is applied at the centre of the left end plate until the failure of the column using displacement control approach. The bi-linear steel material model and “Hashin” damage criteria are deployed to model steel and composite material. Table 1 compares the results obtained from the present analyses and Shaat and Fam’s (2006) test. Good agreement is noticed for both bare steel and strengthened columns with mean ratio and coefficient of variance (COV) of ultimate load are 0.98 and 0.036 respectively. Good agreement is also observed in the case of axial shortening as mean ratio and

COV are 0.99 and 0.031 respectively. The axial load versus displacement curves also exhibit excellent match with the test results as shown in Figure 3(b).

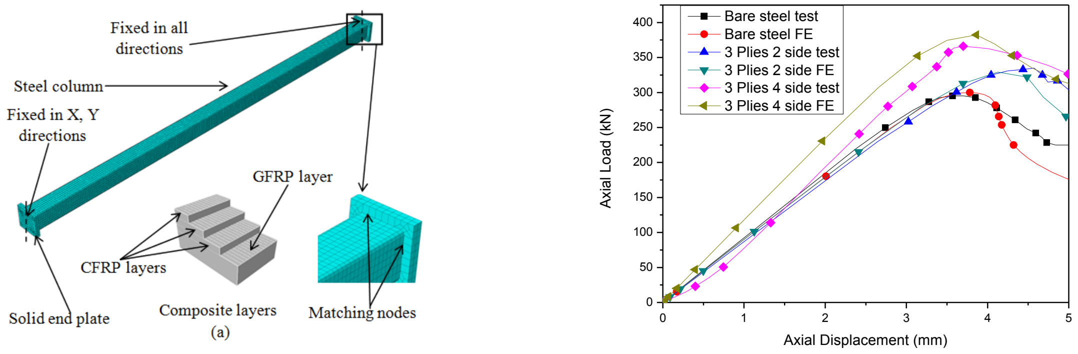


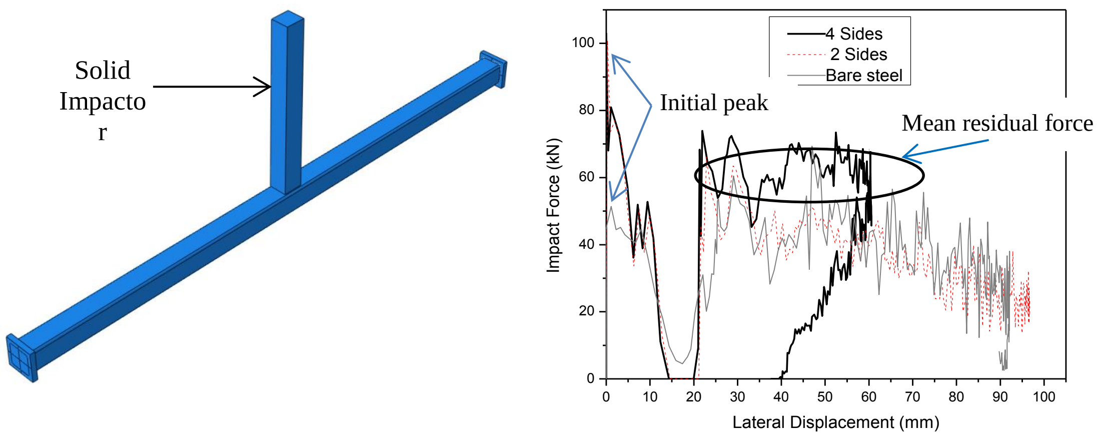
Figure 3. (a) Detail of FE model, (b) Comparison of load-displacement response

Table 1 Comparison between experimental results and present FE analysis

Specimen	*Ultimate Load (kN)*		*Axial shortening at ultimate*		P_{Test} / P_{FE}	U_{Test} / U_{FE}
	Test (P_{Test})	FE (P_{FE})	Test (U_{Test})	FE (U_{FE})		
Control	295	299.81	3.70	3.78	0.98	0.98
2 Sides	335	329.08	4.57	4.13	1.02	1.02
4 Sides	362	382.27	3.70	3.86	0.95	0.96
Mean					0.98	0.99
COV					0.036	0.031

Impact Simulation of CFRP Strengthened Columns

The validated bare steel and strengthened columns are utilised to conduct explicit dynamic analysis due to unavailability of experimental results on the CFRP strengthened columns under transverse impact loading. A cubic impactor is modelled using solid element (C3D8R) with dimensions of 74 × 74 × 700 mm as shown in Figure 4 (a). Impact velocity is applied using the same concept discussed in the 'dynamic impact simulation' section to create an impact collision at the mid height of the column. The surface to surface interaction method is used to define the contact behaviour between the impactor front surface and column outer surface to propagate impact force from impactor to column. The hard and penalty contact algorithm are used to define mechanical contact property. Strain-rates effect is considered by using Cowper-Symonds power law with a multiplier factor of 40.4 s^{-1} and exponent of 5. No strain rate effects are considered in CFRP and GFRP material models. In the case of two sides strengthened column, the top and the bottom portions in Figure 4(a) are strengthened and the other two sides are unstrengthened. The property and geometry of CFRP strengthened column is the same as the validated CFRP strengthened model, regardless of considering the strain rate effects due to dynamic loading. A total of three numerical models are developed and the results are presented in terms of axial displacement, lateral displacement, impact force and failure modes. The value of impact velocity and impactor mass are selected as 7 m/s and 170 kg. The boundary conditions are one end fixed and another end hinge and no axial load is applied.

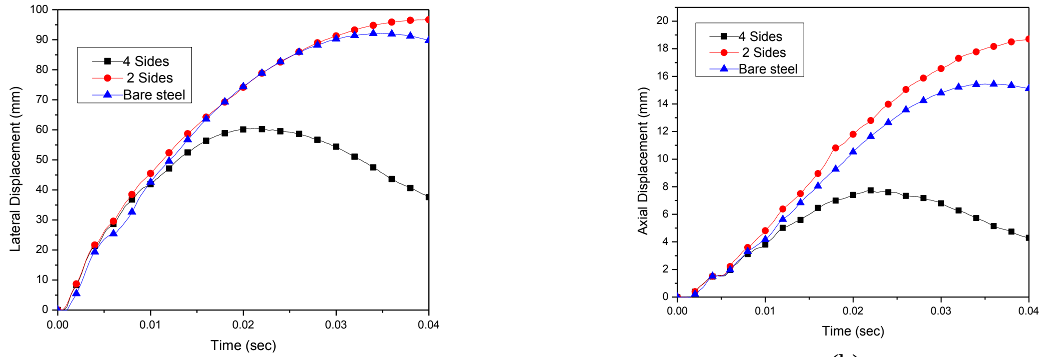


(a) (b)

Figure 4. (a) Numerical model for impact analysis, (b) Impact force-lateral displacement comparison

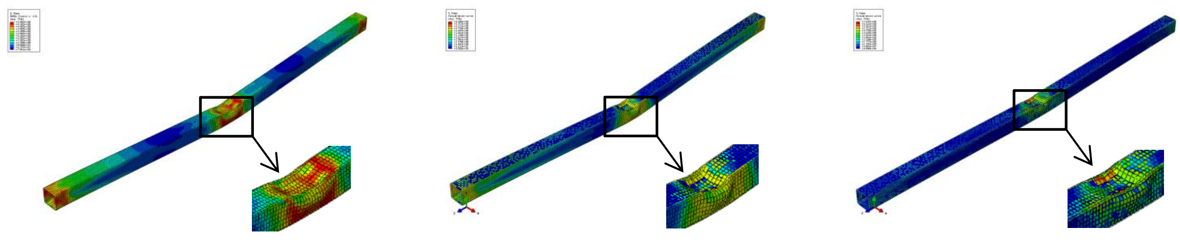
RESULTS AND DISCUSSIONS

Figure 4(b) shows the transverse impact force and lateral displacement curves of bare steel, and strengthened columns. The peak impact forces of bare steel, two sides, and four sides strengthened columns are 51.37 kN, 100.08 kN and 103.89 kN respectively. Thus, CFRP strengthening technique enhances the stiffness of strengthening zone as peak impact force increases about double after strengthening. The mean residual force of four sides strengthened column is higher than the 2 sides and bare steel column. Figure 5 presents the lateral displacement-time and axial displacement-time curves of bare steel and strengthened columns. The permanent lateral and axial displacements of four sides strengthened column are reduced by 58% and 72% respectively compared to the bare steel column. However, the two sides strengthened column shows larger displacements in both transverse and axial directions than the bare steel column. This may occur due to excessive outward buckling of unstrengthened zone as high stress concentration propagates from strengthened regime (impact point) to unstrengthened regime. The two unstrengthened sides of two sides strengthened column show larger outward buckling than four sides strengthened column hence results large axial and lateral displacements. The failure modes of all three types of columns are shown in Figure. 6. The local outward buckling of bare steel and two sides strengthened columns are prominent compared to the four sides strengthened column. Thus four sides strengthened column exhibits better performance in term of energy absorption capacity and buckling control against transverse impact loading. The findings of this numerical simulation are also well agreed with the findings of Jama et al. (2006).



(a) (b)

Figure 5. (a) Lateral displacement-time curves, (b) Axial displacement-time curves.



(a) (b) (c)

Figure 6. Failure modes (a) Control, (b) CFRP- 2 sides, (c) CFRP- 4 sides

CONCLUSIONS

The three dimensional FE models are validated to conduct numerical simulation of CFRP strengthened steel columns. The dynamic impact simulation is performed using the validated model under transverse impact loading at the mid height of the columns. The key findings from the FE analyses are as follows:

- The FE models are developed successfully by comparing the results with the experimental tests. The initial impact forces of strengthened columns increase remarkably. However, the residual force is increased only for four sides strengthened column. Other two types of columns show almost same residual forces.
- The performance of CFRP strengthened column under transverse impact loading is significant as permanent lateral and axial displacements of four sides strengthened column are reduced by 58% and 72% due to strengthening effect.
- In SHS column, CFRP wrapping scheme plays an important role. It has been noticed that only four sides strengthened column shows performance enhancement under impact loading. On the other hand, two sides strengthened column shows larger displacement responses and ineffectiveness due to excessive outward buckling of unstrengthened zone.

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